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The Interaction Between Stereoscopic and Luminance Motion

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An interaction in apparent motion between perceived three-dimensional forms defined by stereopsis and local luminous elements is reported. Vertical stripes of cyclopean square gratings were simulated by random-dot stereograms. Alternation of two-frame stereograms whose phases differed by 90 deg caused two kinds of percepts, planes' motion in depth (first-order stereoscopic motion, first-order SM) or lateral motion of gratings (higher-order stereoscopic motion, higher-order SM). Experiment 1 explored the conditions under which higher-order SM frequently arose, as opposed to local luminance-based in-depth motion (first-order SM). The results show that, when the spatial arrangements of two-frame random dots were correlated, higher-order SM dominated for long ISI conditions (ISI > 73 msec). When they were uncorrelated, higher-order SM dominated even under zero ISI conditions. Subjects reported that, when higher-order SM was seen, dots were attached to the surfaces of the moving cyclopean figure (motion capture). Experiment 2 tested which factor caused the domination of higher-order SM under uncorrelated conditions in Experiment 1, the larger distance of dot jump or the varied directions of the dots' motion. The results show that, when the distance of dot jump is large or when the directions of dots' motion are incoherent, higher-order SM arises more frequently. When local first-order motion signals are weakened by appropriate temporal and spatial conditions or by incoherent motion directions, higher-order SM dominates and it captures the motion of dots. © 1997 Elsevier Science Ltd

Stereoscopic (cyclopean) motion   Short-range motion   Random-dot stereogram   Higher-order motion

INTRODUCTION

The apparent motion of a perceived three-dimensional (3-D) shape suggested by stereopsis is often called "stereoscopic motion (SM)" or "cyclopean motion" (Patterson *et al.*, 1991, 1992; Phinney *et al.*, 1994). Julesz & Payne (1968) first discovered the existence of stereoscopic apparent motion using two alternating random-dot stereograms (RDS). They reported that horizontal or rotational motion was observed without any monocular motion cues. The SM's properties were recently investigated by Patterson *et al.* (1992). They found that SM is mediated by a velocity-sensitive system and that the upper limit of its temporal resolution is 8 Hz. Phinney *et al.* (1994) explored the range of spatial displacements over which stereoscopic apparent motion was perceived and they found that the range is about two to three times larger than that for luminance motion. Even motion aftereffect of SM was reported (Patterson *et al.*, 1994).

Chang (1990), however, showed that there existed conditions for which sequentially presented stereograms with dot patterns that correlate over time did not cause perception of a cyclopean figure's motion. She used RDS which defined a horizontal cyclopean square-wave grating, and used displacements along the vertical dimension to produce apparent motion. According to her report, when the dots did not move and only the binocular disparity changed, cyclopean figures did not seem to move laterally, and motion in depth was seen at the regions in which the disparity changed. In addition, when the dot patterns moved in one direction, the cyclopean figure seemed to move in the same direction, even if the entire stereoscopic cue indicated the opposite direction. Chang (1990) also reported that, when there was no correlation of dot patterns over time (i.e., dynamic RDS), the cyclopean figure's motion was observed. She thought that the dynamic dots caused motion signals without direction information and thus, the stereoscopic cue captured the dots' motion. She concluded that pure SM would not exist independently of luminance motion.

These contradictory results seem to indicate that the relative strength between dots' motion (which includes "no motion") and the cyclopean figure's motion determines the appearance of motion. The apparent motion of luminous random dots has been referred to as short-range motion in contrast with long-range motion (Braddick, 1974; Anstis, 1980). Since short-range motion does not

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occur in a dichoptic presentation, it is considered a lower-level motion process (before binocular fusion). The long-range motion process, however, seems to prefer a recognizable shape but is able to handle more than several degrees of displacements. According to this classification, SM appears to be a typical long-range motion. The rivalry here may be between short- and long-range motion processes.

However, the validity of short- or long-range distinctions is questioned by Cavanagh & Mather (1989) and Cavanagh (1991). They suggested that there exists a continuum between these two extreme motion phenomenon and that a better stimulus distinction is between first- or second-order stimuli. First-order stimuli are defined by luminance or color, whereas second-order stimuli are defined by texture, binocular disparity, contrast or relative motion. Cavanagh *et al.* (1989) demonstrated that such second-order attributes can be motion carriers, reporting interattribute motion perception.

Recently, Lu & Sperling (1995) suggested that there are three independent systems extracting motion: a first-order system that extracts motion from moving luminance modulations; a second-order system that extracts motion from moving texture-contrast modulations; and a third-order system that tracks features. Their results indicate that disparity-driven motion (SM) is third-order (feature-based), and not supported by second-order motion mechanisms that use some motion energy computation. This is consistent with Cavanagh (1995) who suggested that stereo-defined motion needs attentional feature tracking. Interattribute motion (Cavanagh *et al.*, 1989) is considered one type of what Lu & Sperling (1995) call third-order motion. On the other hand, Patterson *et al.* (1994) showed that SM aftereffects transfer to luminance-domain motion, which indicates that the SM process shares its path with the first- or second-order motion process and that SM extraction is "sensing", not "cognition". It has not been resolved yet whether SM should be classified as second- or third-order.

The motion of a cyclopean figure is disparity-driven (i.e., higher-order motion), whereas the motion of individual dots that make up a cyclopean figure is luminance-driven (i.e., first-order motion). In-depth motion caused by disparity changes, as reported by Chang (1990), can be thought of as one type of SM, but it is a result of combining two luminance-based signals from both eyes. In this sense, the in-depth motion of elements should be distinguished from the lateral motion of a cyclopean figure. In this paper, these two kinds of motion caused by disparity changes are defined as follows: one is "first-order SM", which results from viewing a luminance-defined target whose identity is maintained as its disparity changes across frames. The detection of changing disparity and establishment of the target's identity are based on first-order motion processes. The other is "higher-order SM" which is defined as the apparent motion of a perceived cyclopean shape suggested by disparity changes alone. In other words, it is motion seen when there are no other cues for coherent motion but there are changes of binocular disparity distribution across space and time. In its classical form, higher-order SM involves a sequence of frames which depict cyclopean shapes that move across frames, while the random-dot pattern changes entirely from frame to frame (e.g., Julesz & Payne, 1968). In this case, a moving target is identified only by the cyclopean shape itself. Chang's (Chang, 1990) results can be interpreted as follows: under stationary or correlatedly moving dot conditions, the cyclopean figure's motion (higher-order SM) was captured by first-order motion of dots which is favored by zero inter-stimulus-interval (ISI). Consequently, first-order SM was seen.

My hypothesis is that, when signals of higher-order SM and first-order motion of dots (which may produce first-order SM) contradict each other, the two percepts will change from one to the other according to the relative strength of the two systems as defined by the spatio-temporal conditions. For example, first-order motion of random dots is thought to have characteristics of short-range motion processing which detects up to 15 min arc displacement (in Braddick's case) and prefers a short ISI. According to Phinney *et al.* (1994), however, the quality of higher-order SM is still good for 83 msec ISI and 6 deg displacement conditions where short-range motion detectors have low sensitivity. ISIs and displacements of dots seem to be good variables to use to control the strength of first-order motion signals. When they are large, higher-order SM will dominate even if dot arrangements are correlated between frames. When they are small, however, first-order motion will dominate and first-order SM will be observed, as in Chang's (1990) experiment. Experiments 1 and 2 examined this hypothesis using two-frame RDS. In the studies reporting higher-order SM (as noted earlier), they commonly used dynamic RDS, i.e., uncorrelated dots across frames. The reason dynamic RDS is suitable for higher-order SM was investigated in Experiment 2.

EXPERIMENT 1

Method

Subjects. Three subjects participated in Experiment 1. Two were graduate students at Kyushu Institute of Design and had some experience as psychophysical subjects, but were naïve as to the purpose of this experiment. The other was the author. They all had normal or corrected-to-normal visual acuity and also had good stereo acuity.

Apparatus and stimuli. Two frames of RDS were generated by a microcomputer (Sharp CZ-644C) and were presented on two CRT monitors (Sharp CZ-614D) which comprised a mirror haploscope as shown in Fig. 1. The two monitors used the same horizontal- and vertical-sync signals so that the frames for both eyes were completely synchronized. The refresh rate was 55 Hz. The whole display screen subtended about 15.3 deg

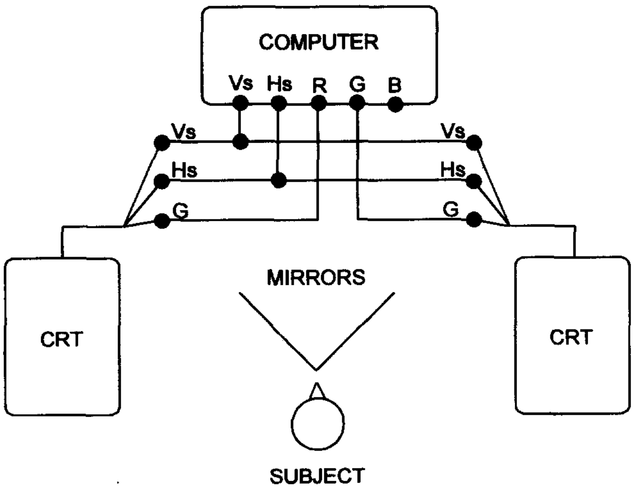

FIGURE 1. The apparatus that creates the SM display. The stimulus was generated by using separate signals for the two eyes and displaying them on two different CRTs using the same vertical- and horizontal-sync signals (Vs and Hs). The color of the dots was the same (green) for both displays and it was provided by the red (R) and the green (G) color guns for the left and the right eyes, respectively.

vertically and 23.0 deg horizontally from a viewing distance of 65 cm. The resolution of the screen was 512×512 pixels. The width and height of the pixels were 2.7 and 1.8 min of arc, respectively. Dots appeared with a probability of 0.01 (i.e., 1%). Each dot was a green bright spot (5.7 cd/m^2), consisting of 2×2 pixels on a dark background. The cyclopean figures were vertical stripes of 3-D square waves in two cycles, as shown in Fig. 2. The display was divided into upper and lower regions and a blank field lay between them. A fixation point having zero disparity was located at the center of the screen. The binocular disparity of the square wave was 5.4 min of arc for the crossed or uncrossed regions. In the first frame, the phases of the upper and lower regions were the same. Then, as each 3-D stripe moved by 90 deg in opposite directions, the phase difference became 180 deg in the next frame. The 90-deg phase shift corresponded to about 2.9 deg shift in visual angle. The manipulation of opposite phase shifting between the upper and lower regions was important in order to discriminate higher-order SM from an artifact of saccadic eye movements. If the perceived directions of both regions were the same, it might have been caused by a saccade which would have affected the motion direction of the entire visible field.

The two frames were alternately and continuously presented with a fixed duration of 182 msec (10 times of monitor refresh) for each frame and with varied ISIs from 0 to 91 msec (0, 1, 2, 3, 4 and 5 times of monitor refresh). Another condition that varied across experiments was the method of generating dot patterns, i.e., "correlated" and "uncorrelated". Under the correlated condition, the spatial distribution patterns of the dots in both frames were the same. Half of the dots were presented exactly in the same places and the other half were horizontally shifted at 5.4 min of arc, thereby producing disparity changes. Under the "uncorrelated" condition, the dot patterns in the two frames were entirely uncorrelated.

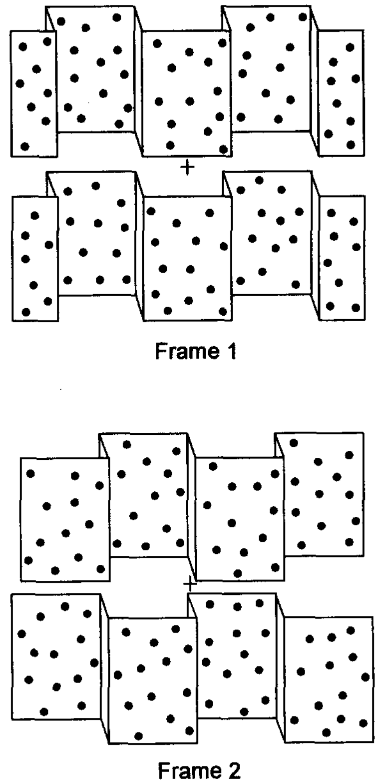

FIGURE 2. A schematic diagram of the stimuli. Two cycles of a 3-D square grating are shown. In the first frame, the phases were the same in both upper and lower regions, and each figure shifted 90 deg of phase in the opposite direction in the next frame. The two frames were alternately displayed over time. The center cross represents the fixation point. The lines that demarcate the rectangular shapes in the figure were not shown in the actual display.

Procedure

The two possible motion percepts are shown in Fig. 3 and were explained to the subjects before the experiment. One was "local motion", which meant that planes of local patches moved in depth only where binocular disparity

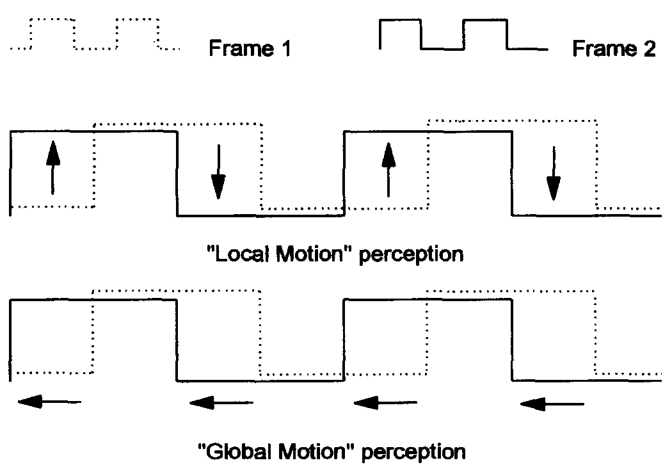

FIGURE 3. Two possible percepts of motion. When first-order motion detection dominates, 2-D motion is determined by the local motion of each dot and, as a result, the "local (in-depth) motion" percept arises in regions where the disparity changes (middle panel). When higher-order SM dominates, the entire cyclopean grating is perceived to move horizontally ("global motion", bottom panel).

changed. The other was "global motion", which meant that the whole stereoscopic forms moved horizontally according to the phase shift of the cyclopean grating. The "local motion" percept indicates domination or capturing of first-order motion signals and the "global motion" percept indicates that of higher-order motion signals.

There were two variables: six ISIs and two dot correlation types. Under each combination of conditions, the relative strength of the two kinds of percepts was measured. One trial consisted of more than 200 successive alternations of frames. Subjects were told to keep pushing an appropriate button according to their percept for as long as that percept lasted. When both types of motion were seen or when they could not decide which percept was stronger, they were told to release both buttons. The period during which subjects pushed both was treated as a period during which they did not push either one. Each trial was paced for each subject, that is, they were first exposed to the motion display, and the timing started when the subject first pushed either button. Then the alternation counting started and the trial ended when it came to 200. This procedure was useful for subjects to achieve binocular fusion and familiarize themselves with the percept of the 3-D figure before timing started. Subjects were told to stop the trials when the perceived 3-D figure collapsed. However, no collapse was ever reported by any of the subjects. It was also explained that if both upper and lower regions moved in the same horizontal direction, the motion should not be considered to be "global motion".

There were two blocks, each of which included twelve (6 ISIs ×2 correlation types) trials. As the buttons were scanned at each frame alternation, the frequency out of 400 sampled data represented the strength of each percept under each condition. The order of trials was randomized within each block. A few trials were done before the experiment as training.

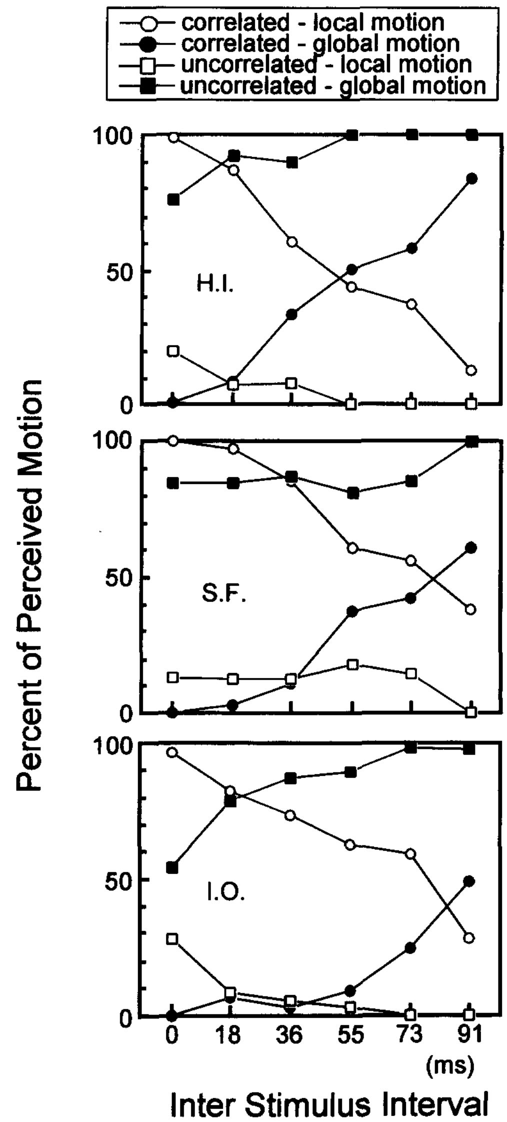

FIGURE 4. The percentages of seeing each type of motion as a function of ISI. Circles and squares represent data under the "correlated" and "uncorrelated" conditions, respectively. Filled and open symbols represent the percentages of perceiving "global motion" and "local motion", respectively. "Global motion" dominated for all subjects when the dots were "uncorrelated", or when ISI was longer than approximately 80 msec.

Results and discussion

The results are shown individually in Fig. 4. The changes of percepts followed the pattern of a typical "figure–ground reversal" experiment. When one percept clearly dominated, it persisted for an extended period and, when the two percepts competed, one frequently changed into the other. The duration for which neither motion was seen accounts for quite a small percentage under each condition for each subject, i.e., 2.3, 1.3 and 13.0% of total tested duration for H.I., S.F. and I.O., respectively.

For all the subjects, under the uncorrelated conditions, even when ISI was zero, "global motion" dominated. This phenomenon was expected because most previous studies which have reported higher-order SM adopted dynamic RDS (i.e., uncorrelated dots between frames). On the other hand, under the correlated condition, when ISI was zero, "global motion" was barely perceived. These results agree with those reported by Chang (1990). However, as ISI increased, the proportion of "global motion" increased and, finally, "global motion" dominated for all the subjects for the 91 msec ISI conditions. As dominance seems to be a monotonic function of ISI, the domination may become clearer also for subjects S.F. and I.O. for ISI values larger than 91 msec. The change of dominance indicates an interaction between first-order and higher-order motion detecting. When ISI was short, there were strong first-order signals that indicated no motion for half of the dots, thus suppressing global higher-order SM. When ISI was long, however, the signals from first-order motion detectors would be weakened (at the same time, the dot's identity would be destroyed) and higher-order SM would capture dot motion. Even if the outputs from the first-order motion detectors remained, they would only indicate that there was no 2-D motion. Chang's (1990) conclusion that, in order to perceive motion in stereo-defined direction, stereoscopic motion cues must be linked to luminance motion signals is doubtful. When "global motion" was seen under longer ISI conditions, subjects reported that the dots seemed to be attached to the surface of the moving 3-D figure, like the motion capture reported by Ramachandran & Cavanagh (1987).

The effect of visual persistence of luminous dots in the results should also be considered. With short ISIs, visual persistence of luminous dots would also establish the identity of each dot between frames, suggesting "no motion" under the correlated conditions. However, as ISI increased, the persistence would also become less important, resulting in the domination of higher-order SM. Both first-order motion detection and visual persistence may be placed in a more general system for luminance motion processing although their relationship has an inhibitory quality, as clearly shown by Watamaniuk (1992). Therefore, even if visual persistence, together with a first-order motion process, plays an important role in the correlated condition, the results still demonstrate an interaction between higher-order SM and luminance-based motion.

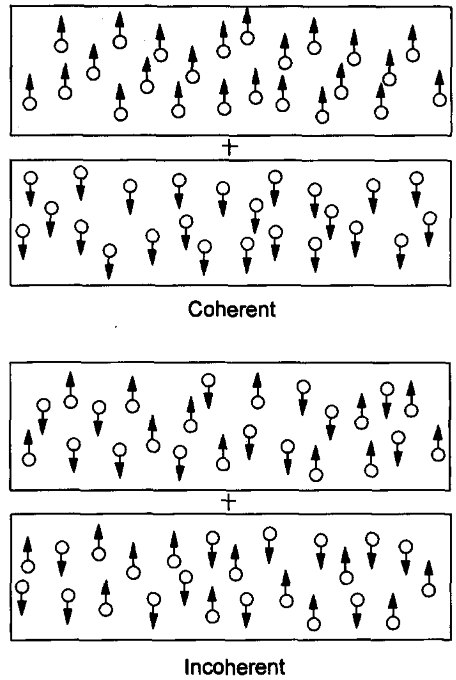

FIGURE 5. "Coherent" and "incoherent" motion conditions. Under the "coherent" motion condition, every dot within the same region jumped in the same direction, and the directions were opposite between the upper and lower regions. Under the "incoherent" motion conditions, every dot in the stimulus randomly jumped up or down. In the next frame, every dot jumped in the reverse direction and returned to its original position under both conditions.

EXPERIMENT 2

Experiment 1 showed that the relative strength between first-order and higher-order SM detection depends on the spatial and temporal conditions. As for the spatial conditions, however, it remains unclear which factor determined the dominance of higher-order SM under the uncorrelated conditions; incoherent directions of dot motion or a larger distance of each dot jump. Under the uncorrelated conditions, as each dot must have moved in a different direction, the motion direction signals may have canceled out each other within a certain area (Chang, 1990). This hypothesis can explain why dynamic RDS are suitable for SM perception, and were successfully used in experiments by other researchers. Otherwise, first-order motion signals might be weakened under the uncorrelated condition because the distance of each dot jump was larger than that under the correlated conditions (where the distance was zero for half of the dots). A large distance of dot jump may have the same effect as a large ISI has on first-order motion detection. Experiment 2 examined the effects of the two factors on the relative strength of the two percepts.

Method

The subjects and apparatus were the same as in Experiment 1. The stimuli were also alternating two-frame RDS with zero ISI. However, the direction and distance of each dot jump were varied. There were two conditions of the motion direction of the dots, i.e., "coherent" and "incoherent" (Fig. 5). Under the coherent conditions, all the dots within the same region jumped in the same vertical direction through the successive frames. However, when all the dots in the upper region jumped downward, all the dots in the lower region jumped upward. The distance jumped was the same in both regions. Then, in the next frame, they jumped in opposite directions and returned to their original positions. However, under the incoherent conditions, each dot in both regions jumped either up or down. In the next frame, the direction of each dot jump was reversed and the dots returned to their original positions. The distance jumped was the same for all the dots. The distance of vertical dot jumps was varied (1, 4, 7 and 10 pixels, corresponding to 1.8–18 min of arc). The display area was always the same; thus, several dots disappeared from or appeared in the area according to the jump. In addition to the vertical jump, half of the dots were shifted 5.4 min of arc horizontally, producing the disparity changes. There were two blocks, each of which included eight trials (2 direction ×4 distance conditions). The other procedures were the same as in Experiment 1.

Results and discussion

The results are shown in Fig. 6. When the distance jumped was 1.8 min of arc, "local motion" dominated under both direction conditions for all the observers. This is not surprising because the situation was quite similar to the "correlated and zero ISI" conditions in Experiment 1. However, as expected, the proportion of "global motion" increased as the distance of the dot jumps increased. This indicates that first-order motion signals were weakened by inappropriate spatial conditions, i.e., a large displacement between frames. This effect is the same as that of the ISIs in Experiment 1. As for the directions, when they were incoherent, "global motion" arose more frequently. First-order motion signals seem to have been weakened

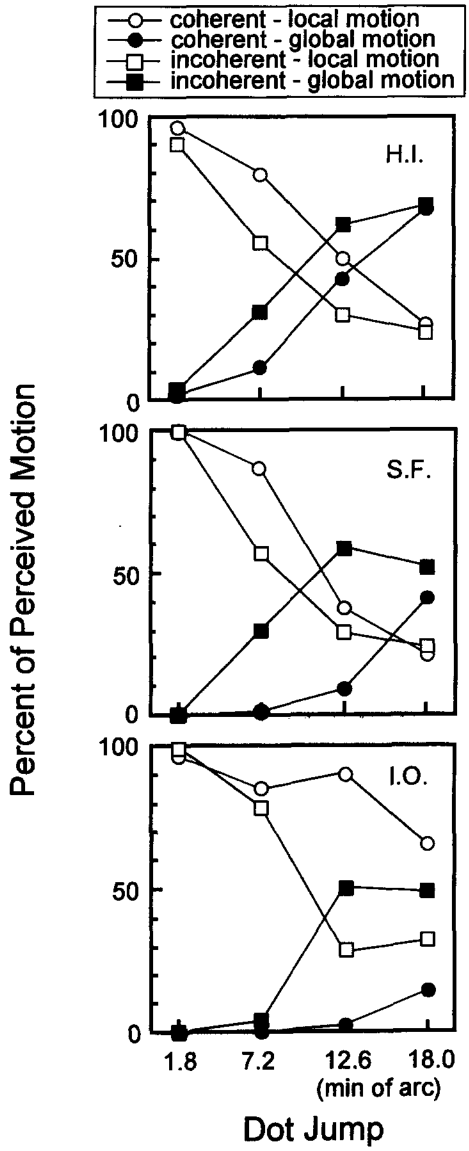

FIGURE 6. The percentages of seeing each type of motion as a function of the distance of dot jump. Circles and squares represent data under the "coherent" and "incoherent" conditions, respectively. Filled and open symbols represent percentages of perceiving "global motion" and "local motion", respectively. "Global motion" became stronger as the distance of dot jump increased. Incoherency also contributes to the increase of the "global motion" percept.

by incoherent dot motion. The summation of local first-order motion signals may have canceled out each other, and the dot motion may have been captured by higher-order SM. If the distance of the dot jump exceeds the limit of "short-range motion", there is little difference between coherent and incoherent conditions, and performance is expected to be the same as that under the "uncorrelated and zero ISI" conditions in Experiment 1. As seen from Fig. 6, jumps greater than 18 min of arc approach this behavior.

Subjects reported that the perception of vertical dot motion survived during "local motion". However, during "global motion" perception under long distance jump conditions, no dot motion was seen and the dots seemed to be attached to the surface of the 3-D figure, as reported in Experiment 1. When motion capture occurred, a suppression mechanism that was working against first-order motion may have been present because vertical dot motion was clearly seen under all conditions when a subject watched the display monocularly. Sometimes, under short-distance jump conditions, vertical dot motion was still seen during "global motion". However, in that case, the motion direction of the dots seemed vertical, not oblique. This seems to indicate that there was no vector summation between the two kinds of motion signals.

GENERAL DISCUSSION

The results of the experiments demonstrate that first- and higher-order SM seem to have similar relative sensitivities to classical first- and higher-order motion mechanisms. First-order SM is favored by short ISIs and small displacements of dots. It is natural because first-order SM is thought to be produced by a combination of first-order signals within each eye. Higher-order SM, however, frequently appeared when ISI or the distance of dot jump was large and when the direction of the dot jump was incoherent. These three factors seem to have weakened first-order motion signals.

One could argue that the strength of higher-order SM signals may also be affected by ISIs. It is possible that higher-order SM is favored by large ISIs. In the literature, however, there are not enough data indicating how ISI affects the strength of higher-order SM, except for Phinney *et al.* (1994), who reported that the D_{max} of SM was larger when ISI was longer. The results here only indicate the relative strength of the two kinds of motion. In the future, the effects of ISIs on higher-order SM should be examined, separately from those effects on first-order motion. In addition, if higher-order SM is velocity sensitive, as shown by Patterson *et al.* (1992), velocity, not ISI, could be a variable that mediates interaction between first-order motion and higher-order SM. In fact, Patterson *et al.* (1992) explained Chang's (1990) results from the perspective of velocity. This hypothesis is worth examining.

One important factor not covered in this paper is the effect of attentional feature tracking (Cavanagh, 1991, 1992, 1995). The stimulus patterns here were cyclic, i.e., the motion direction was predictive for the observers. The long duration of each trial may have allowed some smooth-pursuit eye movements on a certain region. It can also be argued that, even without any conjunctive or vergence movement, one can still track the stimulus pattern by attention. Cavanagh (1995) suggested that stereo-defined motion needs attentional tracking, i.e., the detection of higher-order SM is an active process (note that his display is composed of stationary RDS, which is inappropriate for higher-order SM). Lu & Sperling (1995) also suggested that SM is based on a feature tracking process, as noted earlier. To establish the role of attentional tracking in detecting SM, i.e., whether passive SM processing exists or not, I am conducting some experiments using a constant-stimuli procedure, in which predicted directions of higher-order SM are sometimes incompatible between active and passive processes.

Finally, the similarities and dissimilarities between higher-order SM and first-order motion should be examined further. I treated them as being contradictory in the experimental conditions. However, when luminance motion is not limited to short-range motion, there may be some common characteristics between them. Cavanagh *et al.* (1989) suggested that a common motion process across all attributes (e.g., color, luminance, stereo and texture) exists, which makes it possible to detect interattribute motion. Patterson *et al.* (1991) studied stereo-defined and luminance-defined Ternus displays and showed that perceptual changes according to temporal conditions arose similarly in both figures. This seems to suggest the existence of a common process between stereoscopic and luminance motion, or at least that the two types of motion are processed in a similar way. Recently, Patterson *et al.* (1994) demonstrated that stereoscopic motion aftereffects are transferred to luminance motion. This may be clear evidence of the existence of a common process among them. However, it is also true that both types of motion have their own properties or scales (Cavanagh *et al.*, 1989; Patterson *et al.*, 1992; Phinney *et al.*, 1994). I feel that it is important to study what is common and what is different between each type of motion perception because these can help to determine the whole structure of the general motion processing system.

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